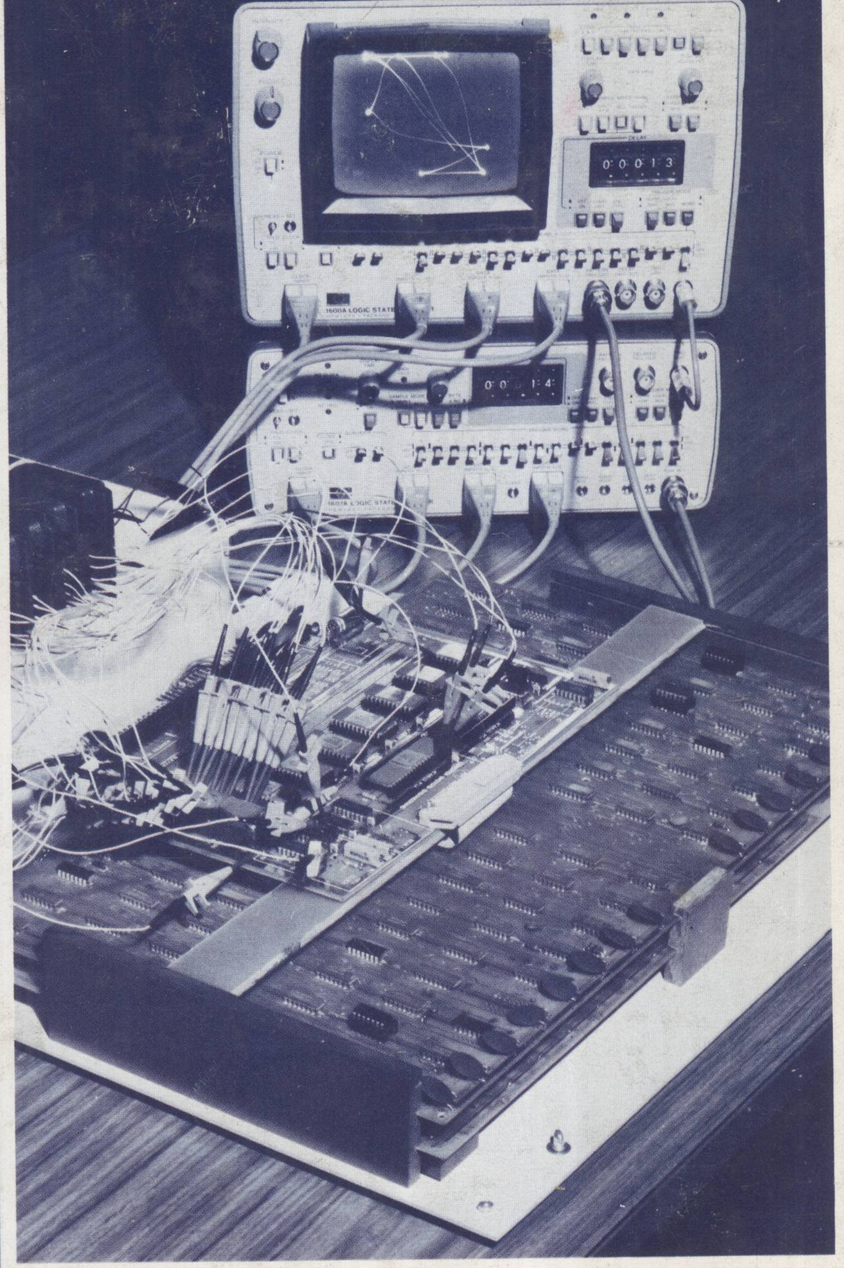

ELECTRONIC MEASUREMENTS

Kantrowitz / Kousourou / Zucker

ELECTRONIC MEASUREMENTS

PHILIP KANTROWITZ, SC. D., P.E., F.A.E.S.

GABRIEL KOUSOUROU, B.S., M.A., P.E.
Professor of Electrical Technology
Queensborough Community College

LAWRENCE ZUCKER, SC. D., P.E.
Associate Professor of Electrical Technology
Queensborough Community College

Prentice-Hall, Inc., Englewood Cliffs, New Jersey 07632

Library of Congress Cataloging in Publication Data

KANTROWITZ, PHILIP.
Electronic measurements.

Includes index.
1. Electronic measurements. 2. Electric measurements. I. Kousourou, Gabriel, joint author.
II. Zucker, Lawrence, joint author. III. Title.
TK7878.K36 621.381'043 78-6140
ISBN 0-13-251769-8

10 9 8 7 6 5 4 3 2

Printed in the United States of America

PRENTICE-HALL INTERNATIONAL, INC., *London*
PRENTICE-HALL OF AUSTRALIA PTY. LIMITED, *Sydney*
PRENTICE-HALL OF CANADA, LTD., *Toronto*
PRENTICE-HALL OF INDIA PRIVATE LIMITED, *New Delhi*
PRENTICE-HALL OF JAPAN, INC., *Tokyo*
PRENTICE-HALL OF SOUTHEAST ASIA PTE. LTD., *Singapore*
WHITEHALL BOOKS LIMITED, *Wellington, New Zealand*

ELECTRONIC MEASUREMENTS

PREFACE

This basic text has been developed as a one-term course in instrumentation to be used in an Associate in Applied Science (A.A.S.) program in a community college, or on a Bachelor of Electrical Technology (B.E.T.) level. The possible expansion of the text to two semesters can depend on the discretion of the instructor. College algebra and some trigonometry are minimum mathematics required for understanding the text material.

The philosophy behind writing such a text is to instruct students in electric and electronic measurements and to introduce the student to any additional, revelant, and important measuring techniques.* Each chapter contains a discussion of the principles of operation, some basic theory, and in some cases a description of some particular instruments. Review questions in each chapter and a glossary of terms appearing at the end of the text will help the student visualize the instrumentation problems.

This text differs from the usual instrumentation text in that primary emphasis is on the measurement rather than the instrument. If the instrument is unique or has special characteristics, then the instrument is discussed.

The material in the text first contains the limiting constraining factors such as sensitivity, reproducibility, accuracy percent error, response, range, etc. The text is also subdivided into groups of the most recent measuring techniques of the various areas in the electronic fields (i.e., meter measurements, transistor devices, digital instrumentation, high-fidelity audio systems and

*All symbols and abbreviations used in this text follow the standard adopted by *IEEE Spectrum*, trade publication of the Institute of Electrical and Electronics Engineers, Inc.

testing, recorders and recording systems, transducer systems, signal generation, applications and measurements, radio frequency systems and testing, etc.). With this approach, the student can understand electronic measurements and make them meaningfully and accurately. This text can also be used by students taking advanced electronic courses.

The authors wish to acknowledge the following for their assistance: Jacqueline Harvey of the Journal of the Audio Engineering Society, New York City, New York; Larry Zide, editor of Sagamore Publishing Co., Inc., Plainview, New York; Milton Aronson, publisher of *Medical Electronics* and *Measurements and Data*, Pittsburgh; Chilton Publishing Co., Radnor, Pennsylvania; John Eargle, audio executive and author, Los Angeles; Dr. Stanley Greenblatt, Microwave Senior Engineer; Al Hancox, Production Manager of Beckman Instrument Co., Schiller Park, Chicago; R. F. Kerzman of Gould Inc., Instrument Systems Division; Kenneth Arthur of Tektronix, Inc., Beaverton, Oregon; Dick Horn of Yellow Springs Instrument Co., Yellow Springs, Ohio; L. C. Lynnworth of Panametrics Inc., Waltham, Massachusetts; Robert Gibson of Endevco Corp., San Juan Capistrano, California; David Berman, Field Engineer of Tektronix, Inc., Beaverton, Oregon; My Jung, Staff Engineer of Hewlett-Packard, Paramus, New Jersey.

The cover concept was developed by Mrs. Ruth Allen of Bayside, N.Y.; the cover photo was provided courtesy of Hewlett-Packard, Palo Alto, California; and the design was completed by the Prentice-Hall Art Department. The authors are grateful to one and all.

Finally, the authors would like to express their appreciation to Cary F. Baker, Jr. and his assistant, Ms. Robin Lavelle; and Donald S. Rosanelli of Prentice Hall Inc. Without their efforts, this book would not have gotten off the ground floor.

The authors wish to dedicate this text to their wives and family: Alice Kantrowitz, Eve and Harry Kousourou, and Jay and Robin Zucker.

PHILIP KANTROWITZ

GABRIEL KOUSOUROU

LAWRENCE ZUCKER

CONTENTS

2

DIRECT CURRENT, VOLTAGE, AND RESISTANCE MEASUREMENTS *11*

3

ALTERNATING CURRENT MEASUREMENTS *52*

4

POWER MEASUREMENTS 75

5

OSCILLOSCOPE MEASUREMENTS 102

6

DISCRETE COMPONENT MEASUREMENTS *139*

7

BASIC SEMICONDUCTOR MEASUREMENTS *165*

8

INTEGRATED CIRCUIT MEASUREMENTS *195*

9

HIGH-FIDELITY AUDIO SYSTEMS AND TESTING *227*

10

RECORDERS AND RECORDING SYSTEMS *261*

11

TRANSDUCER SYSTEMS *292*

1

MEASUREMENT PARAMETERS

1.1 INTRODUCTION

The principal aspects of the scientific method are accurate measurement, selective analysis, and mathematical formulation. Note that the first and most important is accurate measurement. Measurement is the process by which one can convert physical parameters to meaningful numbers. The importance of measurement is simply and eloquently expressed in the following statement by the famous physicist Lord Kelvin: "I often say that when you can measure what you are speaking about and can express it in numbers, you know something about it; when you cannot express it in numbers your knowledge is of a meager and unsatisfactory kind."

The science of measurement has three primary concerns:

1. The establishment of a system of units of measurement.
2. The design, development, and application of instruments and techniques.
3. The interpretation and analysis of the data so that meaningful information is derived.

The form and concept of measurement as we know it today are the ultimate result of a major change in human behavior patterns, which occurred early in human history. Early "civilized" man led a nomadic existence. Since land cultivation had not been introduced, his hunting and animal raising kept him in a constant search for new pastures. With the development of agriculture man began to settle and cluster together in villages. With this new life style there came new necessities. Tents were no longer satisfactory dwellings; more permanent structures had to be constructed. With the advent of these new advances in his craft and the needs arising from a new lifestyle, man required a more accurate measuring process.

1.2 MEASUREMENT PROCESS

The measuring process is one in which the property of an object or system under consideration is compared to an accepted standard unit, a standard defined for that particular property. The number of times the unit standard fits into the quantity being measured is the numerical measure. The numerical measure alone is meaningless unless followed by the unit used, since it identifies the characteristic or property measured.

1.3 FUNDAMENTAL UNITS

To measure an unknown we must have an accepted unit standard for the property that is to be assessed. Since there are virtually hundreds of different quantities that man is called upon to measure, it would seem that hundreds of different standard units would be required. Fortunately this is not the case. By choosing a small number of basic quantities as standards, we can define all the others in terms of these few. The basic units are called *fundamentals*, while all the others are called *derived*. The four fundamental quantities chosen as basic are length, mass, time, and electric current. Length and time, of course, are familiar, whereas mass and current are not quantities which are intuitively obvious—they require some description. A loose definition of mass is the quantity of matter contained in an object. The mass of an object, stationary or moving with a velocity less than that of light, is constant anywhere in the universe. Electric current is defined as the flow of electrons in a conductor. Current will be discussed in great detail in subsequent chapters. There are two rules that govern the choice of a basic unit for a physical quantity:

1. The basic unit must be defined in terms of that quantity which can be measured with the greatest accuracy by available instruments.
2. The basic unit must be reproducible in any well-equipped laboratory using materials and instruments generally found in a laboratory.

1.4 SYSTEMS OF UNITS

Once the fundamental quantities are defined and accepted they are named and a system of units is born. Through the years many systems of units have been proposed and used. In this text we shall use the two systems which now predominate, the S.I. (Système International d'Unite) and the English system. Both systems are based on the four fundamental quantities of length, mass, time, and current. Table 1.1 shows the names of these units in each system. The definitions of the units as listed here are continuously modified as new and more sophisticated measuring methods are encountered.

Table 1.1

	SI	English
Length	Meter m	Foot ft
Mass	Kilogram kg	Slug
Time	Second s	Second s
Current	Ampere A	Ampere A

S.I. System

Meter: The meter is defined as the distance between two fine scratch lines on a platinum-iridium bar kept at the International Bureau of Weights and Measures at Sevres, France. An exact copy is kept at the National Bureau of Standards in Washington. It has recently been defined as 1,650,763.73 wavelengths (in a vacuum) of the orange-red spectrum line of krypton-86.

Kilogram: The standard for the kilogram is a cylinder of platinum-iridium kept by the International Bureau of Weights and Measures in Sevres, France. A duplicate is kept in Washington at the National Bureau of Standards.

Second: The second was originally defined as 1/86,400 part of a mean solar day. The mean solar day is the average value throughout the year for the time interval between two successive noons. It is now defined as 9,192,631,770 periods of a particular radiation of cesium.

English System

Foot: The foot is now defined in terms of the meter, although originally it was one third of the standard yard. Since the meter is now known to a greater accuracy, the foot is defined as 1,200/3,937 (.3048) part of a standard meter.

Slug: The slug is defined as 14.59 kg.

Second: As defined previously.

Note: The units so far defined in both systems are mechanical; the electrical unit of current is the same in both systems, and is defined as follows:

Ampere: The ampere is the magnitude of a current flowing through each of two long parallel conductors separated by a distance 1 m that results in a force between them equal to 2×10^{-7} newtons/meter (N/m) of length.

1.5 DERIVED UNITS

After the system of units has been chosen it is then possible to elicit other necessary units based on these fundamentals, for example, a unit of length multiplied by a unit of length ($m \times m = m^2$ = area). A unit of length cubed ($m \times m \times m = m^3$ = volume) yields a unit of volume. A unit of velocity is obtained by dividing a unit of length by a unit of time (m/s = velocity). These new units which are formed by multiplying or dividing the fundamentals are called *derived.* Any derived unit, no matter how complex, can be traced back to the fundamentals.

Table 1.2 shows the definition and unit name of some of the most common mechanical and electrical derived units. Note that the units are treated as

Table 1.2

Quantity	Unit Name	Definition	Dimensional Analysis
Area	Square meter	m x m	m^2
Acceleration	Meter/s^2		$\frac{m}{s^2}$
Force	Newton	mass x acceleration	$\frac{kg \times m}{s^2}$
Work	Joule	newton x m	$\frac{kg \times m^2}{s^2}$
Power	Watt	$\frac{\text{Joule}}{s}$	$\frac{kg \times m^2}{s^3}$
Charge	Coulomb	ampere x s	
Voltage	Volt	$\frac{\text{Joule}}{\text{coulomb}}$	$\frac{kg \times m^2}{s^2 \times A^2}$
Resistance	Ohm	$\frac{V}{A}$	$\frac{kg \times m^2}{s^3 \times A^2}$
Capacitance	Farad	$\frac{\text{coulomb}}{V}$	$\frac{A^2 \times s^4}{kg \times m^2}$
Inductance	Henry	$\frac{V \times s}{A}$	$\frac{kg \times m^2}{A^2 \times s^2}$
Frequency	Hertz	$\frac{1}{s}$ x cycles	$\frac{\text{cycles}}{s}$

if they were algebraic variables, that is,

$$\mathrm{m} \times \mathrm{m} = \mathrm{m}^2 \quad \text{and} \quad \frac{\mathrm{m}^3}{\mathrm{sec} \cdot \mathrm{m}} = \frac{\mathrm{m}^2}{\mathrm{sec}}$$

Once a unit has been used extensively and has become familiar there is a tendency to forget that that unit has its origins in some manipulations of the fundamentals.

1.6 MULTIPLES AND DIVISIONS OF UNITS

The units in actual use are divided into submultiples for the purpose of measuring quantities smaller than the unit itself. Further, multiples of the unit are designated and named so that measurements of quantities much larger than the unit are facilitated. Table 1.3 presents the prefixes used with the unit when the multiples and submultiples are to be designated. For example, the submultiple of the unit of resistance which is 1/1,000 of an ohm is called a milliohm, and the multiple of the unit ohm which is equal to $10^6\ \Omega$ is called the megohm.

Table 1.3

Prefix	Multiple or Sub-multiple	Symbol
tera	10^{12}	T
giga	10^{9}	G
mega	10^{6}	M
kilo	10^{3}	k
milli	10^{-3}	m
micro	10^{-6}	μ
nano	10^{-9}	n
pico or micro-micro	10^{-12}	p or $\mu\mu$

1.7 UNIT CONVERSIONS

There are times when converting from the multiples or submultiples can be confusing. A few examples will clarify the process.